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Smoothing of diamond-turned substrates for extreme ultraviolet illuminators

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ABSTRACT

Condenser optics in extreme ultraviolet lithography (EUVL) systems are subjected to frequent replacement as they are positioned close to the illumination source, where increased heating and contamination occur. In the case of aspherical condenser elements made by optical figuring/finishing, their replacement can be very expensive (several hundred thousand dollars). One approach to this problem would be to manufacture inexpensive illuminator optics that meet all required specifications and could be replaced at no substantial cost. Diamond-turned metal substrates are a factor of 100 less expensive than conventional aspherical substrates but have insufficient finish, leading to unacceptably low EUV reflectance after multilayer coating. In this work it is shown that, by applying a smoothing film prior to multilayer coating, the high spatial frequency roughness of a diamond-turned metal substrate is reduced from 1.76 to 0.27 nm rms while the figure slope error is maintained at acceptable levels. Metrology tests performed at various stages of the fabrication of the element demonstrated that it satisfied all critical figure and finish specifications as illuminator. Initial experimental results on the stability and performance of the optic under a real EUVL plasma source environment show no accelerated degradation when compared to conventional substrates.

Keywords: Smoothing, diamond-turned optics, Mo/Si multilayers, polyimide, extreme ultraviolet lithography

1. INTRODUCTION

Extreme Ultraviolet Lithography (EUVL) has advanced as the foremost contender among next-generation technologies for high-volume patterning of semiconductor devices and is expected for use in production at the 32-nm node. A key contributor to the successful development of EUVL has been the progress made in recent years in the areas of substrate and reflective coating fabrication for operation at extreme ultraviolet (EUV) wavelengths. EUVL tools require all-reflective camera and illuminator systems, with the majority of the optics operating at near-normal incidence angles, thus requiring multilayer coatings in order to be efficient reflectors. Several of these optical substrates are designed with aspherical surfaces, which are highly difficult to figure/finish within specifications. Although illumination optics have relaxed figure requirements compared to imaging optics, their fabrication -when aspherical- can still be a challenge for substrate manufacturers and thus incur high costs. As an example, a single set of substrates made of conventionally polished silicon for a six-channel aspherical collector optic used in an alpha-class EUVL system[1] cost about half a million US dollars. As an alternative solution, diamond-turned metal surfaces are orders of magnitude less expensive and can be figured to meet specifications as EUVL illuminators. Their finish however, at about 2 nm or higher, reduces their EUV reflectance to only a few percent, thus prohibiting their use. In order to enable use of diamond-turned substrates as EUVL illuminators and potentially lower the overall cost of EUVL systems, this manuscript explores the smoothing of their excessive high spatial frequency roughness and investigates whether such optics are compatible with operation in an EUVL environment.

Smoothing of grazing-incidence, diamond-turned optics for astronomical telescopes[2,3,4] and synchrotron[5] applications in the x-ray wavelength region has been attempted in the past by using lacquer-based films. For the normal-incidence

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EUVL optics discussed in this manuscript a polyimide solution is implemented as the smoothing agent. Polyimides are a family of polymers with properties that include good mechanical strength, excellent high-temperature performance and chemical resistance. For these reasons, they have been used extensively in recent years by the semiconductor industry as passivation coatings, planarization layers in metal lift-off processes and inter-layer dielectrics.

Several designs of EUVL condenser optics have been coated recently at Lawrence Livermore National Laboratory (LLNL) using diamond-turned substrates smoothed by polyimide. One of the optics was chosen for detailed characterization and analysis during all stages of the polyimide-smoothing and multilayer-coating processes, in order to assess its properties. The optic under study is an ellipsoid collector for a "10×" (10:1 reduction ratio) micro-exposure lithographic system located at Sandia National Laboratories (SNL), Livermore, California, and is shown at the bottom of Figure 1.

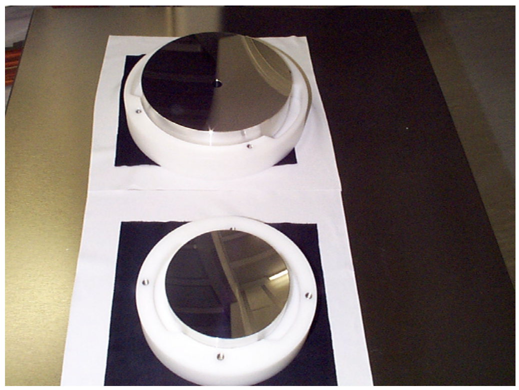


Figure 1: Two different designs of ellipsoid collector mirrors for two SNL 10× micro-steppers are shown after multilayer coating. Both substrates were made of diamond-turned aluminum and were polyimide-smoothed and multilayer-coated at LLNL. Experimental results from the optic shown at the bottom are discussed in detail in this manuscript.

2. EXPERIMENTAL RESULTS

2.1 Substrate smoothing

The collector optic presented in this manuscript (see bottom of Figure 1) had a concave ellipsoidal surface with foci at 110 mm and 1502 mm. The thickness at the outer edge of the part was 25 mm and the outer diameter was 120 mm. The clear aperture (illuminated area) of the optic extended from 10 to 110 mm diameter. The substrate material was diamond-turned aluminum, manufactured by Janos Technology Inc. (Townshend, Vermont). The supplier guaranteed substrate figure accuracy of 60 nm over a radial distance of 25 mm, equivalent to a slope error of 2.5 μrad. The surface finish of the diamond-turned aluminum was measured by atomic force microscopy (AFM) and is discussed later in Section 2.3.

A commercially available polyimide (Durimide™ 285 from Arch Chemicals, Inc.) was used as the smoothing agent. Durimide™ 285 is a pre-imidized, non-photosensitive polyimide, formulated as a gamma-butyrolactone (GBL) solution with 10% solids content. Polyimide was applied on the surface of the diamond-turned aluminum by placing small amounts and by subsequent spinning at 480 rpm for 1 minute. The film was cured at 240º C for 30 minutes in a laboratory vacuum oven purged with N_2, with an additional ramp-up time of 15 minutes in order to reach 240º C from room temperature. This process resulted in a polyimide film thickness of about 3 μm.

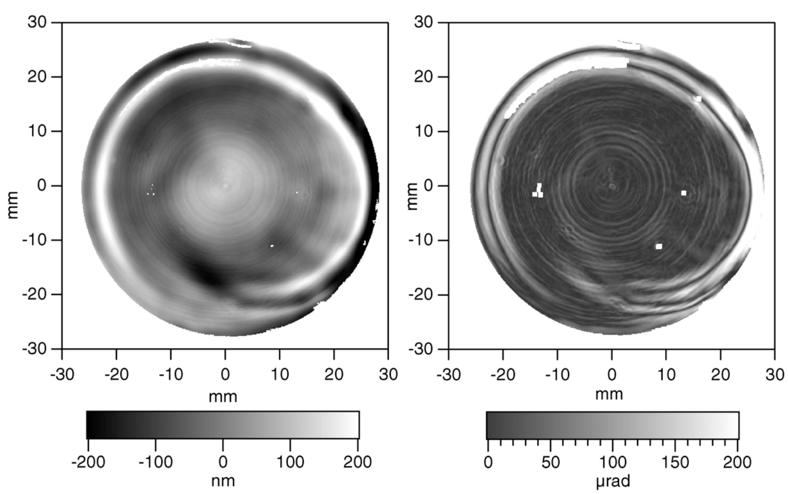
2.2 Multilayer deposition

After application of the polyimide film, the substrate was introduced into a large-scale DC-magnetron deposition system[6] in order to be coated with a molybdenum/silicon (Mo/Si) multilayer. Each Mo/Si bilayer had a thickness of 6.9 nm and the ratio of Mo thickness in the Mo/Si bilayer was 0.4. A total of 80 bilayers were applied and finished with a Si capping layer, resulting in a total multilayer film thickness of 556 nm. The optic was mounted on a platter rotating at speeds of the order of 1 rpm during deposition, which passed alternately under the Si and Mo targets. Thickness control across the substrate was achieved by modulating the rotational speed of the deposition platter while the optic was passing under the sputtering targets. The varying angles of incidence in the design of this optic required a multilayer coating of graded thickness, as is also discussed in Section 2.4. The goal thickness profile was achieved after performing and measuring three test deposition runs, where the velocity modulation algorithm was modified after each iteration in order to achieve the desired results. In addition to the platter motion, the optic was also spun at 400 rpm around its center to average out possible non-uniformities across the surface area of the target materials. Base pressure was maintained at 3×10^{-8} Torr during the deposition run, and the process gas (Ar) pressure was 10^{-3} Torr. The Si and Mo targets were operated at powers of 2000 and 800 Watts, respectively. EUV reflectance measurements of the multilayer-coated optic are presented later in Section 2.4.

2.3 Metrology tests

A portion of the surface figure of the multilayer-coated diamond-turned condenser mirror was measured with a commercial phase-shifting Fizeau-type interferometer with an accuracy of 5 nm rms, operating at the He-Ne wavelength of 633 nm. A transmission sphere was used as a reference surface. Due to the strong aspheric departure of this elliptical condenser, it was possible to measure only the central 55-mm diameter zone of the 110-mm clear aperture. Excessive interferometer fringe density outside that zone prevented getting reliable data there.

A height map of the mirror surface was produced by removing a best-fit ellipsoid from the raw interferometer wavefront data, as is shown in Figure 2(a). This map has a spatial resolution of 0.12 mm. A spiral ridge can be seen near the edge of map, apparently the result of the polyimide spin-coating process. Because slope error is a key requirement of condenser optics, a slope map was constructed from the data shown in Figure 2(a). This slope map was made by the following procedure: (1) the height data were smoothed to a resolution of 0.5 mm in the lateral direction, (2) gradient maps in the x and y directions were constructed by convolving the smoothed heights with 3-by-3 gradient kernels, and (3) the magnitude of the gradient was formed from the square root of the sum of the squared gradient components. Figure 2(b) is the resulting slope map. Most of the surface has a slope less than 50 µrad, but again there are several steeper spiral ridges near the edge of the map.



(a) **(b)**

Figure 2: **(a)** Height map, and **(b)** slope map used to calculate the PSD and rms slope error of the condenser optic. The isolated white regions appearing on the height and slope maps represent invalid data points collected by the interferometer.

As a final step in processing the interferometer data, the power spectral density (PSD) and an rms slope were computed for the height data shown in Figure 2(a). The PSD was formed in the usual way by first calculating a two-dimensional Fourier power spectrum of the height data. This spectrum was then averaged azimuthally around zero spatial frequency to produce a PSD with purely radial spatial frequency dependence. This result is shown later in Figure 3. The following relation was used to calculate the rms slope for spatial periods ranging from 1 to 10 mm:

$$m^2 = \int_{f_1}^{f_2} (2\pi f)^3 S(f)\, df \quad , \tag{1}$$

where m is the rms slope, f is the spatial frequency, $f_1 = 0.1\ \mathrm{mm}^{-1}$, $f_2 = 1.0\ \mathrm{mm}^{-1}$, and S(f) is the surface PSD. For the height map shown in Figure 2(a) the rms slope calculated from equation (1) is 100 μrad. This level of slope error is substantially worse than the initial 2.5 μrad rms of the bare diamond-turned aluminum, as-delivered from its manufacturer (see Section 2.1). The spiral features in the interferometry maps of Figure 2 indicate that the single origin of the excess slope error is the polyimide spin-coating process. The Mo/Si multilayer deposited on top of the polyimide is not expected to contribute to the slope error, since at such low spatial frequencies the multilayer film basically replicates the topography of the substrate[7].

The PSD of the optic in the mid-spatial frequency region was measured using a Zygo New View™ optical profiling microscope. Scans were performed with three objective lens magnifications: 2×, 10×, and 40×, in order to access the spatial period range from 1mm to 5 μm. The optic was tested prior to polyimide application (bare diamond-turned aluminum substrate) and after the Mo/Si multilayer coating. In the high spatial frequency region, measurements were performed with a Digital Instruments Dimension 5000™ atomic force microscope (AFM) using 2×2 μm^2 and 10×10 μm^2 scans at three stages: (i) on the bare diamond-turned aluminum substrate, (ii) after polyimide application on the substrate, and (iii) after the final multilayer-coating. In each of the optical profilometry and AFM tests, three radial locations on the optic (r = 15, 30 and 40 mm) were measured. The resulting PSDs among the three locations were in excellent agreement with each other, indicating uniform finish across the surface for all fabrication steps of this mirror.

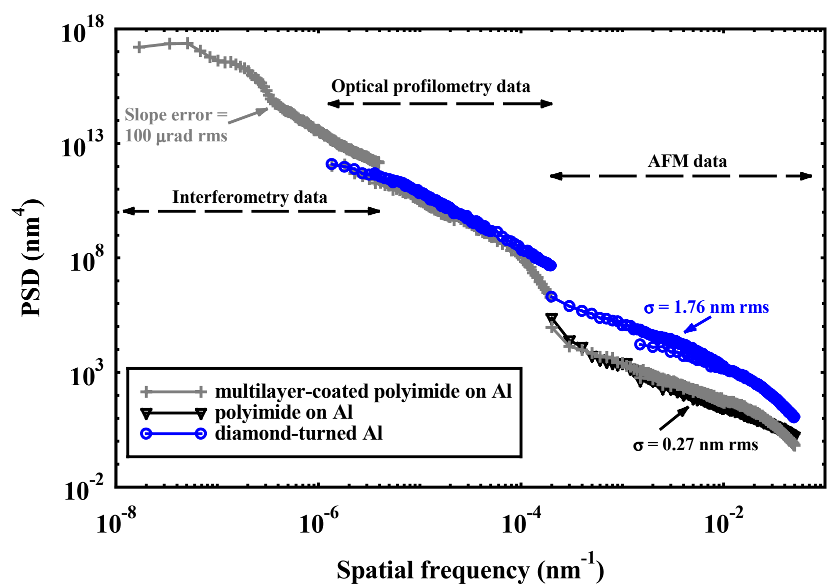


Figure 3: The experimental PSD spectrum of the condenser mirror is plotted over a wide spatial frequency range at three stages of fabrication. Each of the PSD curves obtained from optical profilometry and AFM data is an average over measurements in three radial locations on the surface.

In order to construct the PSD of the optical surface in a wide spatial frequency range, the individual PSD curves determined from interferometry, optical profilometry and AFM measurements are combined and plotted in Figure 3. The AFM data in Figure 3 demonstrate that the polyimide achieved significant smoothing of the high spatial frequency roughness σ given by the expression

$$\sigma^2 = \int_{f_1}^{f_2} 2\pi f S(f) df \quad , \tag{2}$$

where f is the spatial frequency and S(f) is the surface PSD. From equation (2), using the AFM-measured PSD curves plotted in Figure 3 and $f_1 = 10^{-3}$ nm^{-1}, $f_2 = 5\times10^{-2}$ nm^{-1} (the frequency range where it is customary to quote high spatial frequency roughness for EUVL optics) it is determined that on the bare diamond-turned aluminum surface the roughness is σ=1.76 nm rms, while after coating with polyimide the roughness becomes σ=0.27 nm rms. Furthermore, the predicted EUV reflectance loss (absolute) due to scattering after multilayer coating with Mo/Si (as described in Section 2.2) is ΔR=55% on the diamond-turned aluminum substrate, while after smoothing with polyimide it becomes ΔR=2.3%. The impact of polyimide on the surface is thus dramatic since a diamond-turned aluminum substrate without the smoothing effects of polyimide would be too inefficient and practically unusable as EUV reflector. Figure 3 also shows that the AFM-measured PSDs of the polyimide-coated and subsequently Mo/Si-coated surface are essentially identical, thus demonstrating that the Mo/Si multilayer did not significantly affect the smoothing. This result was expected from earlier studies of multilayer growth: DC-magnetron sputtered Mo/Si films remove roughness only at very high spatial frequencies (greater than 2×10^{-2} nm^{-1}), and largely preserve the topography of the substrate at lower spatial frequencies[8]. Therefore, smoothing of the roughness in the mid- and high spatial frequencies up to about 2×10^{-2} nm^{-1} should be attributed to the polyimide film only.

In the plots of Figure 3 there is a significant amount of smoothing apparent in the mid-spatial frequency region around f = 10^{-4} nm^{-1} (spatial period 1/f = 10 μm) exhibited as a "knee" in the PSD curve of the coated surface. This feature is absent in the corresponding PSD curve of the diamond-turned aluminum surface. In order to verify the validity of this effect, two-dimensional images were compared side-by-side from the optical profilometry measurements that were used to determine the PSD curves. The results are shown in Figure 4. Parallel marks with a periodicity of about 10 μm are apparent on the bare aluminum surface shown in Figure 4(a), most likely a result of the diamond-turning polishing process. These marks are not present in the coated surface measurements shown in Figure 4(b), an effect that is attributed to polyimide smoothing as discussed in the previous paragraph. Thus, the "knee" in the coated surface PSD in the region around f = 10^{-4} nm^{-1} in Figure 3 is related to polyimide-smoothing of polishing marks with spatial periods of about 10 μm.

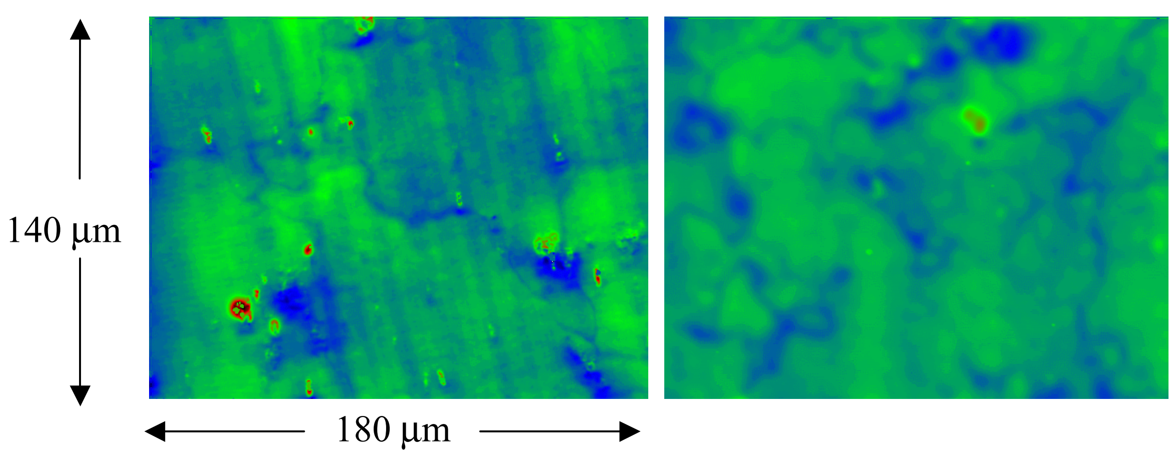


Figure 4: Surface measurements at a radial location r=15 mm on the surface are shown from the Zygo New View™ optical profiling microscope operated at 40× objective lens magnification (a) on the bare, diamond-turned aluminum substrate and (b) after polyimide and multilayer-coating. Images were extracted from the Zygo New View™ instrument data using the TOPO software package[9].

Finally, the multilayer-induced smoothing occurring at very high spatial frequencies is analyzed in Figure 5, showing the high-frequency portion of the AFM-measured PSDs for the polyimide and multilayer-coated surfaces (which have also been plotted earlier in Figure 3). The two curves cross each other at f = 3×10^{-2} nm^{-1}, marking the frequency range (f >3×10^{-2} nm^{-1}) where smoothing due to the Mo/Si multilayer coating dominates over polyimide smoothing. A stochastic film growth model formulated for vapor phase processes[8,10] is used to describe the properties of the DC-magnetron deposited Mo/Si film. According to the model, the PSD of the grown multilayer film (PSD^{film}) is given by the expression

$$PSD^{film}(q) = \Omega \frac{1-\exp(-2\nu\, dq^n)}{2\nu\, q^n}, \qquad (3)$$

where q=2πf, Ω is the sputtered particle volume, ν is related to the lateral distance over which particles can relax, d is the film thickness and n is an exponential parameter characteristic of the type of film growth. In earlier studies[8], n=4 has been established as the characteristic exponent for DC-magnetron sputtering film growth; a smoothing mechanism with n=4 has also been associated with surface diffusion processes in the literature[11]. Given a film with PSD^{film} grown on a substrate with PSD^{sub}, the overall PSD of the top film surface (PSD^{top}) is given by[8]

$$PSD^{top} = PSD^{film} + \alpha^2 PSD^{sub}, \qquad (4)$$

where

$$\alpha^2(q) = \exp(-\nu\, dq^n) \qquad (5)$$

is the replication factor from the substrate to the film. PSD^{top} is calculated in Figure 5 using equations (3)-(5) with parameters Ω = 0.055 nm^3, ν = 4.1 nm, n=4. The AFM-measured PSD of the polyimide substrate was implemented in equation (4) as initial PSD^{sub}. Equation (4) was applied recursively for the entire multilayer stack of N=80 bilayers of Mo/Si with d=6.9 nm bilayer thickness and a final Si capping layer as described in Section 2.2. The calculation results are in very good agreement with the AFM-measured PSD of the multilayer-coated surface.

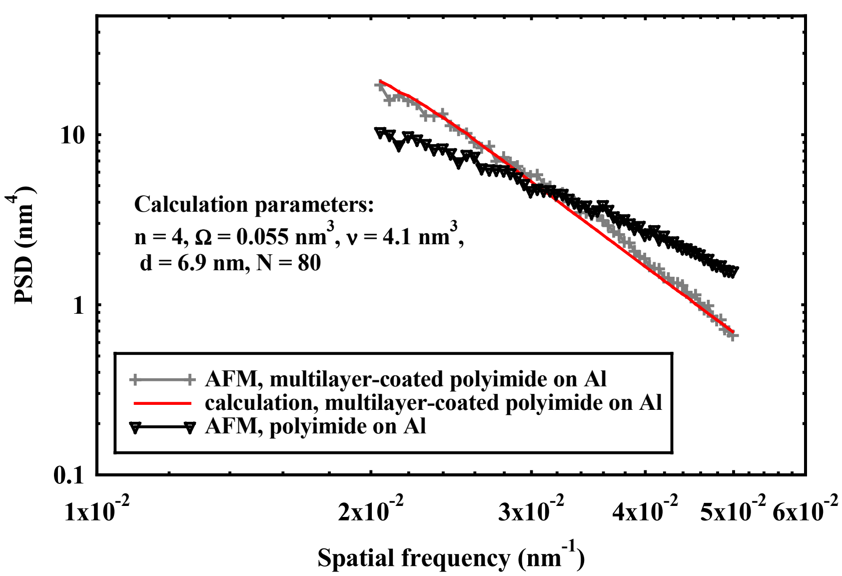


Figure 5: The experimentally measured PSD of the top multilayer surface ("+" data points) is plotted against a calculation (solid line) using the measured substrate PSD (triangle data points) and a thin film growth model[8,10].

2.4 EUV reflectance measurements

The EUV reflectance of the Mo/Si-coated optic was measured at beamline 6.3.2. of the Advanced Light Source. The reflectometer capability at this beamline has been described in detail elsewhere[12]. EUV reflectance measurements were performed at a fixed angle of 8° from normal incidence. The centroid wavelengths of the measured Bragg peaks at each radial point on the surface were normalized to determine the experimental thickness profile plotted in Figure 6. The experimental centroid wavelength was 13.355 nm, obtained after translating the measured wavelengths to the actual angles of incidence across the optic surface, ranging from 1.2° at 5 mm to 13.0° at 55 mm radius, and averaging all the measured points. The peak reflectance is also shown vs. radius in Figure 6 and the average value is R = 64.3%. This result is consistent with the substrate metrology results on the high spatial frequency roughness discussed in Section 2.3.

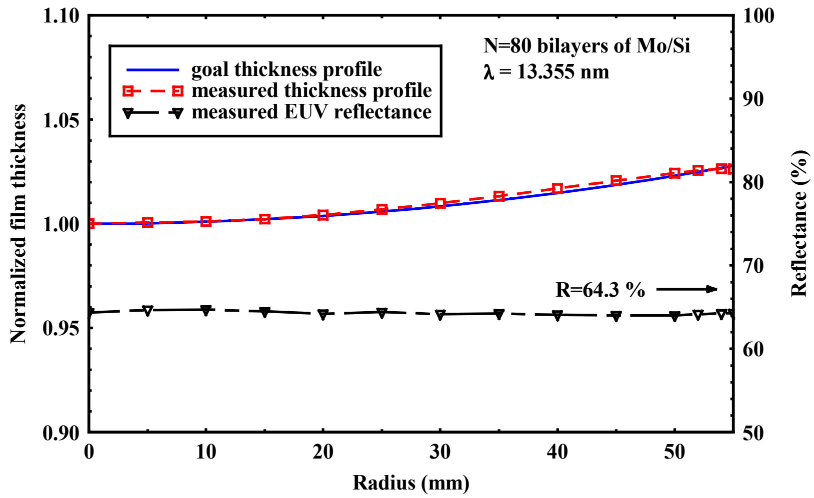


Figure 6: Experimental results on the thickness profile (left y-axis), peak EUV reflectance (right y-axis), and centroid wavelength of the multilayer-coated condenser optic, obtained at beamline 6.3.2. of the Advanced Light Source synchrotron.

2.5 Exposure to EUVL source environment

One of the potential concerns regarding polyimide-smoothed condenser substrates is that the harsh conditions of the EUVL source environment might cause accelerated degradation of the smoothing film and the multilayer coating. A side-by-side comparison with conventional substrates was thus designed as an initial test of the stability and outgassing properties of these elements. A one-inch diameter aluminum disk smoothed with polyimide using the process described in Section 2.1 and a silicon wafer (conventional substrate) were coated with N=10 bilayers of Mo/Si, with each bilayer 6.9 nm thick, and exposed to the EUVL laser-produced plasma source[13,14] located at Sandia National Laboratories, Livermore, California. A pulsed Nd:YAG laser of 1064 nm wavelength was used, manufactured by TRW, Inc. The laser operated at 500 Watts of power and delivered pulses of 8 ns length at a repetition rate of 1.667 kHz. The laser pulses impinged on a liquid xenon spray jet target, with a conversion efficiency of 0.2% into 2π steradians and 2.5% bandwidth. The two samples under study were placed inside the source chamber at a distance of 15 cm away from the source nozzle, with unobstructed view of the plasma, and were exposed to 11.5 million EUV pulses. Considering that several hundred million pulses are usually applied in order to assess optics lifetime inside the EUVL tool[13], the overall number of pulses that the witness samples were exposed to is not considered particularly high. However, even with 11.5 million pulses the present test was deemed harsh given that the number of Mo/Si bilayers on the samples was only N=10, compared to N=40 or more that exist on actual EUVL optics. It was calculated that the two witness substrates coated with N=10 bilayers of Mo/Si were exposed to about 40 times higher intensity of EUV in-band and out-of-band radiation compared to substrates with N=40 bilayers of Mo/Si coating.

The EUV reflectance of the two samples was measured at beamline 6.3.2. before and after exposure in the EUVL source chamber, and the results are shown in Figure 7. Both samples exhibited similar EUV reflectance losses, most likely due to contamination and/or erosion processes. The widening of the EUV reflectance peak was also similar between the two samples, and was attributed to removal of top layers of the Mo/Si multilayer due to erosion[15]. Comparing the effects of EUVL source exposure on the EUV reflectance of the two samples thus revealed no signs of accelerated degradation of the polyimide-coated sample vs. the conventional sample. Outgassing was also monitored inside the source chamber and remained below detection limits throughout this experiment. The same result was observed during an earlier exposure, where polyimide-coated witness flats with the polyimide surface exposed (i.e: without any multilayer coatings) were introduced inside the source chamber and tested for outgassing. Although preliminary, the exposure tests described in this Section eliminated the possibility of rapid degradation or serious incompatibility of polyimide-coated substrates with the EUVL source environment, and are thus positive for further exploration of this technology for EUVL illuminator substrates.

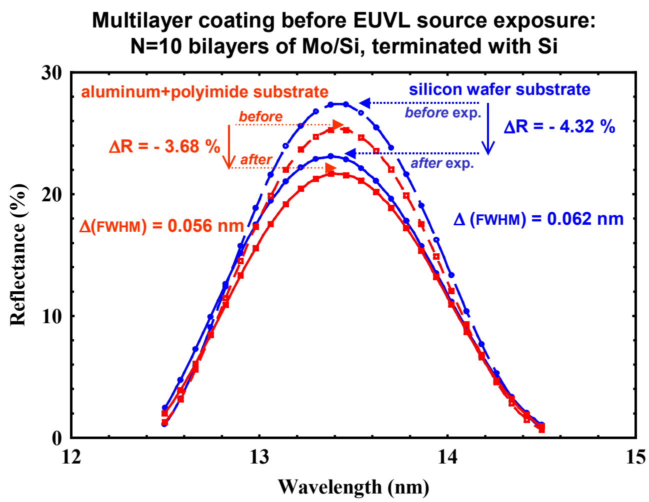


Figure 7: EUV reflectance results from a polyimide-coated and a conventional (silicon wafer) sample, before and after exposure in the EUVL plasma source environment. The effects of the source on the EUV reflectance of both samples are quite similar.

3. CONCLUSIONS

The smoothing properties of polyimide on large-area, diamond-turned aluminum substrates are investigated in a wide spatial frequency range. The results demonstrate substantial smoothing of the high spatial frequency roughness, thus enabling operation of these elements as near-normal incidence EUV reflectors. The metrology and EUV source exposure results presented in this work are quite promising for the use of diamond-turned, polyimide-smoothed optics as normal incidence condenser elements in EUVL tools. Implementation of such inexpensive optics could substantially lower the cost of developing and operating EUVL source/illuminator systems, and thus accelerate EUVL commercialization.

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[15] A detailed discussion of the complex processes taking place in the EUVL source environment and causing degradation of illuminator optics is beyond the scope of the present manuscript.